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Summary of hints for new physics from (quark) flavour physics

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Recently two hints for new physics have emerged: The B_s mixing phase ϕ_s and the rate of $D_s \rightarrow (\mu, \tau)\nu$ exposing a discrepancy of $\sim 3\sigma$ and 3.8σ deviation from the Standard Model respectively. Moreover the difference of the CP asymmetries in $B \rightarrow K\pi$ between the charged and neutral modes is at the 5.3σ level which is somewhat larger than expected. New physics in ϕ_s or $A_{CP}(B \rightarrow K\pi)$ would be in contradiction with the minimal flavour violation hypothesis. The latter has recently attracted attention because of the absence of deviation in CP and flavour violation in the quark sector.

Status of quark flavour physics^a

Quark flavour physics in the Standard Model (SM) is governed by the four parameter CKM matrix describing the strength of flavour transitions. The two least known parameters are embedded in the normalized CKM triangle, which has been (over)constrained by experimental facilities like CLEO, BaBar, Belle, Tevatron, NA48 and others over the last few years. It is well known that CP-violation is one of the three necessary conditions for Baryogenesis. In the SM the CKM sector is the only established source of CP-violation, which is found to be insufficient (roughly ten orders of magnitude) in the three family case due to small quark mass differences in the up and down type structures. This renders CP-violation a promising territory to search for new physics (NP). On the other hand all the measurements from flavour facilities result in constraints which are consistent with the SM, depicted in the by now famous plots of the CKM-fitter and UT-fit collaborations². In short, the CKM mechanism is self-consistent with the current data and describes CP-violation of B_d and K mesons quantitatively^b.

It might be seen as a consequence of this consistent picture that the community has focused on rare decays and minimal flavour violation (MFV), which we intend to discuss briefly.

The term “rare” is understood to be relative to the SM and it could be loop suppressed (flavour changing neutral currents (FCNC)), helicity suppressed (small quark mass), $SU(2)_L$ (right-handed currents) or simply CKM suppressed (often called Cabibbo suppressed). The prototype of a flavour changing neutral current is the $b \rightarrow s\gamma$, where experiment and theory are in agreement. The potential of many observables (FCNC) has not been experimentally exhausted or not even seen yet by the B -factories BaBar and Belle and this fact is one of the many reasons why the upgrade at Belle and a Super B -factory is necessary in order to pursue the search for new physics in particle physics. In the very near future the LHCb experiment⁵ will open the window to the B_s -sector^c and reach particularly far in channels with muons in the final states, e.g. measurement of the B_s mixing phase to be discussed below, $B_s \rightarrow \mu\mu$, $B_s \rightarrow \phi\gamma$ ⁶ and $B_{d(s)} \rightarrow K^*(\phi)\mu\mu$ ⁷.

^aA summary on new results in the field has been given by Barsuk¹ at Moriond QCD 2008.

^bCP-violation in the D and B_s systems are not established at the 5σ level. First CP-asymmetry measurements in the Baryon sector have been reported at Moriond $A_{CP}(\Lambda_b^0 \rightarrow p\pi^-[K^-]) = 0.03(17)(5)[0.37(17)(3)]$ ³

^cThe exciting results from the Tevatron represent only the very beginning of B_s -physics.

The idea behind the minimal flavour hypothesis is that the only sources of violation of the global flavour symmetry $G_F = U(3)^5$ are the Yukawa matrices. This symmetry can be formally recovered by promoting the Yukawas to spurious fields transforming accordingly under G_F . This allows MFV to be defined as an effective field theory⁸, which is formally invariant under G_F . The theory is minimal in the sense that the Yukawas remain the only source of flavour violation. In the original paper no new sources of CP-violation were assumed, but within the MSSM for instance certain authors have allowed for new CP phases which show up in dipole operators. The concept of MFV is appealing, experimentally motivated and testable because it predicts correlations among observables due to a small number of possible operators. An interesting result is for instance that MFV imposed on the R-parity violating MSSM evades the bounds from Proton decay⁹ and in this connection is a viable alternative to R-parity itself.

A model generating a MFV structure is basically equivalent to a model explaining the masses and flavour violations. This has proven to be a notoriously difficult area where simple ideas are sparse. Furthermore if the spurious Yukawa matrices are thought to be degrees of freedom acquiring a vacuum expectation value then some of them correspond to Goldstone bosons and require a yet unknown mechanism for generating their mass. In order to assess the large hierarchy between the top Yukawa as compared to the other flavours it was recently proposed¹⁰ to consider the consecutive breaking of the quark flavour group $G_F|_\Lambda \rightarrow SU(2)_{Q_L} \times SU(2)_{U_R} \times SU(3)_{D_R} \times \dots|_{\Lambda'} \rightarrow 1^d$ at the scales Λ and Λ' such that $\Lambda/\Lambda' \sim m_t/m_b$.

*Non-standard $D_s \rightarrow l\nu$ decays?*¹¹

In the SM the rate of leptonic decays as $D_s \rightarrow l\nu$ is simply given by

$$\Gamma(D_s \rightarrow l\nu) \sim |V_{cs}|^2 f_{D_s}^2 \cdot G_F^2 m_l^2 m_{D_s} \left(1 - \frac{m_l^2}{m_{D_s}^2}\right)^2, \quad (1)$$

exposing the famous helicity suppression factor $(m_l/m_{D_s})^2$ familiar from $\pi \rightarrow l\nu$. This helicity suppression is relieved in decays $D_s \rightarrow D_s^*(\gamma) \rightarrow l\nu(\gamma)$ but should not contaminate the process $l = \mu$ by more than one percent and is entirely negligible for $l = \tau$ ^{12,13,14}. In practice the product $f_{D_s}|V_{cs}|$ is constrained and if one quantity is known it allows us to determine the other one.

Initially the plan was to validate the precision of lattice QCD in the semileptonic charm sector in order to gain confidence for predictions in the B -sector and to extract $|V_{ub}|$ from $B \rightarrow \tau\nu$ with predictions for f_B for instance.

The story is now a different one. The HPQCD collaboration has provided precise predictions,

$$f_{D_s}^{HPQCD} = 241(3) \text{ MeV}, \quad f_{D^+}^{HPQCD} = 208(4) \text{ MeV}, \quad (2)$$

with 2+1 staggered fermions (and therefore unquenched)¹⁶. Averaged measurements from CLEO, BaBar and Belle¹⁷ with the SM relation $|V_{cs}| \simeq |V_{ud}| = 0.97377(27)$ leads to a decay constant

$$f_{D_s}^{exp} = \begin{cases} 274(10) \text{ MeV}^{13} \\ 277(09) \text{ MeV}^{14} \end{cases}, \quad (3)$$

where the first average excludes certain measurements with potentially problematic normalizations to the $D_s \rightarrow \pi^+\phi$ mode. The experimental and HPQCD predictions differ by more than 3σ , in fact 3.8σ in the analysis presented in¹⁴. The 2 Higgs Doublet Model (2HDM) of type II, most prominently embedded in the MSSM, is an example of a model which is sensitive to this channel. The decay rate gets modified by a multiplicative factor $[1 - (\tan\beta m_{D_s}/m_{H^+})^2 (m_s/(m_c + m_s))]^2$,

^dWe are taking a cavalier attitude to additional $U(1)$ factors above.

which shows destructive interference and therefore has the wrong characteristic to explain the effect^e. There is also a term from the right-handed coupling of the up-type quarks proportional to m_U , which adds constructively but is negligible due to a suppression factor $(m_{D_s}/m_{H_+})^2$ (independent of $\tan\beta$ in the rate), at least in more standard 2HDM's¹⁴. In general though the helicity suppression could be relieved in other models of NP, but the separate average of the μ and τ channels clearly contradicts

$$f_{D_s}^{exp(\mu\nu)} = 273(11) \text{ MeV}, \quad f_{D_s}^{exp(\tau\nu)} = 285(15) \text{ MeV}^{14}, \quad (4)$$

this hypothesis as it is the τ and not the μ channel which leads to a larger decay constant! The situation has become even more interesting as very recently CLEO has released data on $D_+ \rightarrow \mu_+\nu$ ¹⁸ from where they extract

$$f_{D_+}^{exp} = 205.8(8.5)(2.5) \text{ MeV}, \quad (5)$$

which is in rather good agreement with the HPQCD values in (2). It should be added that the prediction of f_{D_+} is in principle more challenging than f_{D_s} as the former contains a (chiral) u quark which is harder to simulate on the lattice than the s quark in f_{D_s} . Decay constants can also be determined by QCD sum rules to a precision of about 10-15% which clearly cannot compete with the uncertainties of the prediction given in Eq. (3). The results are consistent within uncertainties¹⁹. Moreover QCD sum rules predictions have generally been lower than lattice predictions for the decay constants f_{D,D_s,B,B_s} and this qualitative pattern remains for the prediction in Eq. (3) and therefore does not constitute a source of doubt on the results. It is not natural for models of NP to give rise to enhancement in the second generation (s, c) but none in the first family (u, d). In reference¹⁴ non-standard interactions in S, T, U -channel were proposed: $W'/\text{charged Higgs}$, leptoquarks with charges $+2/3$ and $-1/3$. In principle the phenomenon could also be explained by an enhancement of $|V_{cs}| \sim 1.1$, which would contradict unitarity in many models. Let us finish this section by noting that in principle the recently proposed Lee-Wick Standard Model allows for CKM elements larger than one²⁰ without violating unitarity. In practice though, the effect can only be significant in the top elements because of the possible closeness of the top mass to a NP scale.

New phase in B_s oscillations?

Neutral meson oscillations are a fascinating phenomenon often setting strongest constraints on NP models in the flavour sector and are a realization of EPR correlations. Of the four possible oscillation modes K_0, B_d, B_s, D_0 the third and fourth were only established in the last two years. If a final state f can be reached from both meson and anti meson, e.g. $B_s \rightarrow f \leftarrow \bar{B}_s$, the mixing can be observed in time dependent decay rate. In order to give the reader an idea, we shall display a rate

$$\Gamma(B_s(\bar{B}_s) \rightarrow f) \sim \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos(\phi_s) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) \pm \sin(\phi_s) \sin(\Delta M_s t),$$

for a case with no relative strong phases and where the ratio of mixing coefficient p and q is $|p/q| \simeq 1$ ²¹. The latter is the case in the SM and in nature²¹. Needless to say that the sign difference in the $\sin(\phi_s)$ term is crucial in connection with B_s -tagging. The mass and width difference $\Delta M_s, \Delta\Gamma_s$ and the relative phase difference between the mass and width transition elements $\phi_s \equiv -\arg(\Gamma_{12}/M_{12})$ are observables. The phase ϕ_s , which is often called mixing phase, is an unambiguous signal of CP-violation and is predicted to be

$$\phi_s^{SM} \simeq -2\beta_s \equiv 2 \arg[V_{ts}V_{tb}^*/(V_{cs}V_{cb}^*)] \simeq -2\lambda^2\eta \simeq -0.04(1) \simeq -2.0(5)^\circ, \quad (6)$$

^eC.f. reference¹⁵ for a first numerical analysis in conjunction with the MSSM and the CLEO-c experiment.

in the SM. It is an example of a good observable as the prediction is “very clean” and it is highly sensitive to NP. Measurements of ΔM_s and $\Delta\Gamma_s$ do not indicate deviation from the SM at the current experimental or theoretical precision⁴.

Recently D0²² and CDF²³ have published results from time-dependent angular analysis on the tagged decay $B_s \rightarrow J/\Psi\phi$, which allows constraints to be set on $\Delta\Gamma_s$ and ϕ_s . These results were combined by the UTfit-collaboration²⁴ with previous measurements. The result is parameterized in terms of the NP phase ϕ_{B_s} ($\phi_s \equiv \phi_s^{SM} + 2\phi_{B_s}$ ^f) with the fit result in the Bayesian approach of

$$\text{UTfit}^{24}: \quad \phi_{B_s} = -19.9(5.6)^\circ. \quad (7)$$

Out of a two-fold ambiguity we have quoted the result which is consistent with information on strong phases from $B \rightarrow J/\Psi K^*$ by invoking the approximate $\text{SU}(3)_F$ symmetry^g. The first result deviates by 3.7σ from the SM^h. At a recent workshop the UTfit collaboration has given an update of their results, using new partial results of D0 dropping an $\text{SU}(3)_F$ assumption, resulting in $\phi_{B_s} = -18(7)^\circ$ and a 2.7σ deviation from the SM²⁶. At the very same workshop CKM-fitter has presented a preliminary analysis, assuming Gaussian distributions in the absence of more precise information of D0ⁱ, with a 2.7σ effect of NP in ϕ_s ²⁶. It should be added that the combination of the two results is not straightforward since D0 uses information on strong phases from $B \rightarrow K^* J/\Psi$ and $\text{SU}(3)_F$ and CDF does not. In particular D0 and CDF have not yet published the combination of their results but are of course working on it.

“Large” difference of CP asymmetries in $B \rightarrow K\pi$ in charged and neutral mode?

The non-leptonic decay $B \rightarrow K\pi$ is a loop dominated decay and therefore sensitive to NP. There has been a tension at the 2σ level between ratios of branching fraction in charged and neutral modes. The focus has moved to the CP-asymmetries in that mode²⁷

$$\begin{aligned} A_{\text{CP}}(B^0 \rightarrow K^+\pi^-) &= -0.097(12), \quad A_{\text{CP}}(B^+ \rightarrow K^+\pi^0) = 0.050(25) \\ \Rightarrow \Delta A_{\text{CP}} &\neq 0 \text{ @ } 5.3\sigma, \end{aligned} \quad (8)$$

as emphasized in two recent articles in Nature by BaBar and Belle²⁸. It is worth mentioning that the results are averages of measurements by BaBar, Belle, CDF & CLEO in the neutral mode and BaBar & Belle in the charged mode and that the individual measurements are all consistent with each other. Again in order to give the reader an idea we write down the topological decomposition,

$$\begin{aligned} \mathcal{A}(B^0 \rightarrow K^+\pi^-) &= -Te^{i\gamma} - P \\ \sqrt{2}\mathcal{A}(B^+ \rightarrow K^+\pi^0) &= -(T + C + A)e^{i\gamma} - P - P_{EW}, \end{aligned} \quad (9)$$

in the isospin limit which relates certain amplitudes with each other. The symbols T and C denote Cabibbo suppressed tree graphs and C stands for color suppressed, P is the QCD emission & annihilation penguin, P_{EW} is the electroweak penguin and A is the tree annihilation graph. In this decomposition we have omitted the color suppressed electroweak penguin since it is not crucial for the essence of the argument. A large difference in the CP asymmetries could be caused by C , A or P_{EW} . The issue is that the contributions of C and A are difficult to estimate

^fWe use the sign convention for ϕ_s from CDF and D0, which is opposite to the one by the UTfit collaboration.

^gThe $\text{SU}(3)_F$ limit might not work too well because the ϕ contains a singlet component contrary to the K^* .

^hThe first paper pointing towards a discrepancy in the global B_s system within a global analysis is reference²⁵. The authors found a 2σ discrepancy (without the tagged analysis).

ⁱAccording to them this tends to underestimate the errors.

precisely within QCD and P_{EW} is sensitive to NP, since the amplitude for a hypothetical quark grows with $m_t'^2/m_Z^2$ due to the famous GIM enhancement effect.

The crude estimate of the hierarchies from naive factorization $|P| : |T|, |P_{\text{EW}}| : |C| \simeq 1 : \lambda : \lambda^2$ with $\lambda \simeq 0.2$ was given a long time ago²⁹. To estimate $|A|$ is more difficult but it can for instance be argued that the annihilation of the B -meson is proportional to its wave function which is known to be small from quark models. In QCD factorization (leading heavy quark limes) the annihilation term is color suppressed and only the small 'tree' Wilson coefficient contributes; From the tables in³⁰ we infer $|A/T| \lesssim 0.1^j$. Altogether this suggests that the two CP asymmetries in (8) are small ($O(\lambda)$ times a strong phase suppression) and very close to each other. The former is the case but not the latter and this is at the heart of the "new $B \rightarrow K\pi$ puzzle".

A closer look appears appropriate. Fits of general isospin parameterization in $B \rightarrow K\pi$ to all observables (branching ratios, (time-dependent) CP asymmetries) were undertaken recently in the neutral mode in³¹ and in the charged and neutral modes in³². In order to reduce the number of parameters below the number of observables^k, quantitative results including error estimates have been taken into account, e.g. ratio of $P_{\text{EW}}/(C+T)$ from QCD factorization³⁰. In reference³² the fits constrain $|(C+A)/(T-A)|$ to the range of $[0.52, 3.0]$ with a central value 0.89. Whereas this certainly challenges the old estimates $|C/T| \sim 0.2, |A/C| \sim 0.2$ ²⁹, the situation in QCD factorization appears less pressing; $|C/T| \sim 0.28_{-0.2}^{+0.3}$ at NLO³³ and $|A/T| \lesssim 0.1$ ³⁰ (C and A add mostly constructive in QCD factorization). The first result comes with large, and presumably conservative, parametric uncertainty and the latter is difficult to judge because of its model dependence due to endpoint divergences. In summary these results allow for speculations but not for conclusions. In reference³³ a different point was emphasized. Even in the case where the strong phases are tuned to satisfy Eq. (8), the time dependent CP asymmetry $S_{\pi_0 K_s}$ still differs from the SM by 2σ . The same qualitative statement can also be inferred from the explicit formulae in section 3.5.1. of reference³².

If it shall turn out that there is really a discrepancy then an enhanced electroweak penguin P_{EW} would constitute a primary suspect for NP contributions. In this connection the fourth generation was emphasized³⁴, because of the $m_t'^2/m_Z^2$. It was argued that enhanced P_{EW} could accommodate the large CP asymmetry as well as the deviation in the measurement of the B_s mixing phase and be of primary interest for electroweak Baryogenesis.

Conclusions

Of the three puzzles presented here, the ϕ_s mixing phase will presumably be resolved earliest as the LHCb experiment will determine the phase to a precision of $\sim 2^\circ$ for a nominal luminosity in one year. In connection with the decay constant f_{D_s} it would certainly be desirable to have a verification of the result by groups using other methods of simulating QCD on the lattice. On the experimental side the BES-III experiment will determine f_{D_s} with an uncertainty of about 2%³⁵, meeting the theoretical precision advocated by HPQCD¹⁶, after four years of operation at nominal luminosity of $5 \text{ fb}^{-1}/\text{year}$. Experimental progress on $\Delta A_{\text{CP}}(K\pi)$ puzzle, mostly needed in $K^+\pi^0$ channel (8), will mainly come from e^+e^- machines since the hadronic machines as the LHCb are unsuitable to detect a π^0 in terms of two photons. As already stated before, deviations in ϕ_s and $A_{B \rightarrow \pi K}$ would contradict the popular MFV hypothesis and therefore be of utmost importance.

We would like to end this write-up by mentioning that in choosing three examples we have made choices and have for instance left out the tension between the $\sin(\beta_{\text{eff}})$ determination from

^jThis ratio was estimated to be $O(\lambda^2)$ prior to QCD factorization, e.g. ²⁹.

^kIn the total $B \rightarrow K\pi$ (isospin limit) system there are 11 parameters exceeding the 9 observables.

the tree dominated decay $B \rightarrow J/\Psi K_s(b \rightarrow c\bar{c}s)$ and penguin dominated decay $B \rightarrow \phi K_s(b \rightarrow s\bar{s}s)$ ⁴. Recently constraints on $\sin(2\beta)$ were obtained from $\Delta M_s/\Delta M_s$ and ϵ_K (improved lattice result) and with and without $|V_{ub}/V_{cb}|$, which deviate in $\sin(2\beta)$ from the two decay types above in by $1.8\text{-}2.7\sigma$ ³⁶. The status of $(g-2)_\mu$ has been discussed at a dedicated session at the conference³⁷.

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